

# An accretion disc-corona model for X-ray spectra of active galactic nuclei

Xinwu Cao

*Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai, 200030, China; E-mail: cxw@shao.ac.cn*

Accepted 2008 December 9. Received 2008 December 8; in original form 2008 September 15

## ABSTRACT

The hard X-ray emission of active galactic nuclei (AGN) is believed to originate from the hot coronae above the cold accretion discs. The hard X-ray spectral index is found to be correlated with the Eddington ratio  $L_{\text{bol}}/L_{\text{Edd}}$ , and the hard X-ray bolometric correction factor  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  increases with the Eddington ratio. The Compton reflection is also found to be correlated with the hard X-ray spectral index for Seyfert galaxies and X-ray binaries. These observational features provide very useful constraints on the accretion disc-corona model for AGN. We construct an accretion disc-corona model and calculate the spectra with different magnetic stress tensors in the cold discs, in which the corona is assumed to be heated by the reconnection of the magnetic fields generated by buoyancy instability in the cold accretion disc. Our calculations show that the magnetic stress tensor  $\tau_{r\varphi} = \alpha p_{\text{gas}}$  fails to explain all these observational features, while the disc-corona model with  $\tau_{r\varphi} = \alpha p_{\text{tot}}$  always leads to constant  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  independent of the Eddington ratio. The resulted spectra of the disc-corona systems with  $\tau_{r\varphi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  show that both the hard X-ray spectral index and the hard X-ray bolometric correction factor  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  increase with the Eddington ratio, which are qualitatively consistent with the observations. We find that the disc-corona model is unable to reproduce the observed very hard X-ray continuum emission from the sources accreting at low rates (e.g.,  $\Gamma \sim 1$  for  $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$ ), which may imply the different accretion mode in these low luminosity sources. We suggest that the disc-corona system transits to an advection-dominated accretion flow+disc corona system at low accretion rates, which may be able to explain all the above-mentioned correlations.

**Key words:** (galaxies:) quasars: general—accretion, accretion discs—black hole physics

## 1 INTRODUCTION

It is believed that active galactic nuclei (AGN) are powered by accretion of matter on to massive black holes, and the observed UV/optical emission of AGN is thought to be a thermal emission from the standard geometrically thin, optically thick accretion discs (e.g., Shields 1978; Malkan & Sargent 1982; Sun & Malkan 1989). On the other hand, the power-law hard X-ray spectra of AGN are most likely due to the inverse-Compton scattering of soft photons on a population of hot electrons (Galeev, Rosner & Vaiana 1979; Haardt & Maraschi 1991, 1993). In the accretion disc-corona model, such soft photons are from the cold disc, a fraction of which are Compton scattered by the hot electrons in the corona above the cold disc to the hard X-ray energy band. The disc-corona model was extensively explored in many previous works (e.g., Svensson & Zdziarski 1994; Haardt & Maraschi 1991, 1993; Kawaguchi, Shimura & Mineshige 2001; Liu, Mineshige & Shibata 2002; Liu, Mineshige & Ohsuga 2003). In this disc-corona scenario, most gravitational energy is generated in the cold disc, probably through turbulence produced by the magneto-rotational instability (Balbus & Hawley 1991). The

magnetic fields generated in the cold disc are strongly buoyant, and a substantial fraction of magnetic energy is transported vertically to heat the corona above the disc with the reconnection of the fields (e.g., Di Matteo 1998; Di Matteo, Celotti & Fabian 1999; Merloni & Fabian 2001, 2002). It was found that the temperature of the hot electrons in the corona is roughly around  $10^9$  K, which can successfully reproduce a power-law hard X-ray spectrum as observed (e.g., Liu, Mineshige & Ohsuga 2003).

The physical processes of turbulence triggered by the amplified magnetic fields in the disc are very complicated, and quite unclear, though they are revealed to some extent with numerical magneto-hydrodynamical (MHD) simulations (Balbus & Hawley 1991, 1998). The so-called “ $\alpha$ -prescription” is widely adopted in most of the works on accretion discs (Shakura & Sunyaev 1973), in which the magnetic stress tensor is assumed to be proportional to the total pressure ( $p_{\text{tot}} = p_{\text{gas}} + p_{\text{rad}}$ ), gas pressure  $p_{\text{gas}}$ , or  $\sqrt{p_{\text{gas}} p_{\text{tot}}}$  (Sakimoto & Coroniti 1981; Stella & Rosner 1984; Taam & Lin 1984). The magnetic stress tensor  $\tau_{r\varphi} = \alpha p_{\text{tot}}$  was suggested in Shakura & Sunyaev (1973), however, the disc is thermal unstable if the radiation pressure dominates over the gas pressure (Shakura & Sunyaev 1976)(but also

see Hirose, Krolik & Blaes 2008). It was argued that the magnetic field amplification is likely to be limited to that the magnetic pressure is less than the gas pressure even in the inner radiation-pressure-dominated regions, i.e.,  $\tau_{r\varphi} = \alpha p_{\text{gas}}$  (Sakimoto & Coroniti 1981). The disc with this stress tensor is thermal stable (Sakimoto & Coroniti 1981). The stress tensor  $\tau_{r\varphi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  was initially suggested by Taam & Lin (1984) based on the idea that the viscosity is proportional to the gas pressure, but the size of turbulence should be limited by the disc scaleheight that is given in terms of the total pressure. This is also supported by the analysis on the local dynamical instabilities in magnetized, radiation-pressure-supported accretion discs (Blaes & Socrates 2001), which also leads to  $p_m = B^2/8\pi \simeq \beta_0 \sqrt{p_{\text{gas}} p_{\text{tot}}}$ , where  $p_m$  is the magnetic pressure, and  $\beta_0$  is a constant of the order of unity (see Merloni & Fabian 2002, for a detailed discussion). Nayakshin, Rappaport & Melia (2000) argued that the accretion disc model with  $\tau_{r\varphi} = \alpha p_{\text{gas}}$  is too stable to explain the unstable behaviour observed in GRS 1915+105, and they further suggested that it is possible to couple the radiation to the particles through collisions and thereby allow the radiation pressure to contribute to the stress tensor to some extent. As the complexity of the physics in the radiation-pressure-dominated fluids, any one of these stress tensors should only be regarded as a possible option in accretion discs.

The hard X-ray observations on AGN may provide useful clues on the accretion disc-corona models. Wang, Watarai & Mineshige (2004) compiled a sample of radio-quiet AGN, and found a strong correlation between  $L_{2-10\text{keV}}/L_{\text{bol}}$  and  $L_{\text{bol}}/L_{\text{Edd}}$ , which was conformed by Vasudevan & Fabian (2007) with a different AGN sample. This correlation was then used to constrain the disc-corona models with different magnetic stress tensors, and they found that the model with magnetic stress tensor  $\tau_{r\varphi} = \alpha p_{\text{gas}}$  is favored by the correlation of  $L_{2-10\text{keV}}/L_{\text{bol}} - L_{\text{bol}}/L_{\text{Edd}}$ . It was also found that the spectral index of hard X-ray continuum emission is correlated with the Eddington ratio (Lu & Yu 1999; Wang, Watarai & Mineshige 2004; Shemmer et al. 2006, 2008). Zdziarski, Lubinski & Smith (1999) found a strong correlation between the Compton reflection and the hard X-ray spectral index for Seyfert galaxies and X-ray binaries. In the accretion disc-corona scenario, the hard X-ray emission originates from the Compton scattering of the soft photons by the hot electrons in the corona. Therefore, the correlations of the hard X-ray spectral index with the Eddington ratio/Compton reflection, together with the correlation of  $L_{2-10\text{keV}}/L_{\text{bol}} - L_{\text{bol}}/L_{\text{Edd}}$ , provide important constraints on the accretion disc-corona model.

The parallel plane homogeneous corona is unable to produce an X-ray spectrum with  $\Gamma < 2$  in 2–10 keV. The X-ray photons radiated from the corona are reprocessed in the cold disc, and the reprocessed photons irradiate the corona, which cool the corona and lead to rather soft X-ray spectra with  $\Gamma \gtrsim 2$ . In the patchy corona model proposed by Haardt, Maraschi & Ghisellini (1994), the corona appears as individual blobs above the cold disc. Most of the reprocessed photons do not enter the blob, so the cooling is significantly reduced and the blobs are hotter than the parallel plane homogeneous corona, which leads to harder X-ray spectra. This model can explain the observed hard X-ray spectra with  $\Gamma < 2$  in some AGN (e.g., Zdziarski et al. 1996), however, it is still unable to explain the correlation between the Compton reflection and the hard X-ray spectral index for Seyfert galaxies and X-ray binaries (Zdziarski, Lubinski & Smith 1999), which is also the case for the parallel plane homogeneous corona model.

Zdziarski, Lubinski & Smith (1999) suggested that a central hot plasma surrounded by a cold disc may explain the correlation of the Compton reflection with the hard X-ray spectral index. In this scenario, the cold disc is truncated at a certain radius  $d$ , within which the hot plasma may possibly correspond to an advection dominated accretion flow (ADAF) (e.g., Narayan & Yi 1995). The radiation of the hot plasma is dominated by the inverse Compton scattering of the soft photons from the outer cold disc, while the cold disc is irradiated by the inner hot plasma. Thus, the Compton reflection component decreases with increasing the inner radius of the cold disc, which leads to less soft seed photons from the cold disc entering the hot plasma and then the harder X-ray spectrum from the hot plasma. The correlation between the Compton reflection and the hard X-ray spectral index can be reproduced by this model (see Zdziarski, Lubinski & Smith 1999, for the details). An alternative model was proposed by Beloborodov (1999) to explain the correlation between the Compton reflection and the X-ray spectral index. In this model, the hot plasma above the cold disc is assumed to move away from the cold disc at a mild relativistic velocity. Such an outflow reduces the downward flux, and then reduces both the reflection and reprocessing in the cold disc. The reduction of the reprocessing leads to less incident soft seed photons and cooling in the hot plasma above the cold disc, and in turn leads to harder X-ray spectrum (Beloborodov 1999; Malzac, Beloborodov & Poutanen 2001).

In this work, we take these different magnetic stress tensors as candidates in our disc-corona model calculations, which could be tested with the X-ray observations of AGN. We summarize the disc-corona model in Sect. 2, and the numerical results of the model calculations are given in Sect. 3. In Sect. 4, we discuss the physical implications of the results.

## 2 THE DISC-CORONA MODEL

The gravitational power dissipated in unit surface area of the accretion disc is given by

$$Q_{\text{dissi}}^+ = \frac{3}{8\pi} \dot{M} \Omega_K(R)^2 \left[ 1 - \left( \frac{R_{\text{in}}}{R} \right)^{1/2} \right], \quad (1)$$

where  $\dot{M}$  is the mass accretion rate of the disc,  $\Omega_K(R)$  is the Keplerian velocity at radius  $R$ , and  $R_{\text{in}} = 3R_S$  (Shakura & Sunyaev 1973). The Schwarzschild radius  $R_S = 2GM_{\text{bh}}/c^2$ , where  $M_{\text{bh}}$  is the black hole mass. The corona is assumed to be heated by the reconnection of the magnetic fields generated by buoyancy instability in the disc.

The power dissipated in the corona is (Di Matteo 1998)

$$Q_{\text{cor}}^+ = p_m v_p = \frac{B^2}{8\pi} v_p, \quad (2)$$

where  $p_m$  is the magnetic pressure in the disc, and  $v_p$  is the velocity of the magnetic flux transported vertically in the disc. The rising speed  $v_p$  is assumed to be proportional to their internal Alfvén velocity, i.e.,  $v_p = b v_A$ , in which  $b$  is of the order of unity for extremely evacuated magnetic tubes.

The soft photons from the disc are Compton scattered by the hot electrons in the corona to X-ray bands, and about half of the scattered photons are intercepted by the disc. The reflection albedo  $a$  is relatively low,  $a \sim 0.1 - 0.2$ , and most of the incident photons from the corona are re-radiated as blackbody radiation (e.g., Zdziarski, Lubinski & Smith 1999). Thus, the energy equation for the cold disc is

$$Q_{\text{diss}}^+ - Q_{\text{cor}}^+ + \frac{1}{2}(1-a)Q_{\text{cor}}^+ = \frac{4\sigma T_{\text{disc}}^4}{3\tau}, \quad (3)$$

where  $T_{\text{disc}}$  is the effective temperature in the mid-plane of the disc, and  $\tau = \tau_{\text{es}} + \tau_{\text{ff}}$  is the optical depth in vertical direction of the disc. In this work, we adopt  $a = 0.15$  in all our calculations.

As the detailed physics for generating magnetic fields in the accretion disc is still quite unclear, we adopt different magnetic stress tensors as:

$$\tau_{r\varphi} = p_m = \begin{cases} \alpha p_{\text{tot}}; \\ \alpha p_{\text{gas}}; \\ \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}, \end{cases} \quad (4)$$

in our model calculations, respectively. We summarize the equations describing the disc as follows:

The continuity equation of the disc is

$$-4\pi R H_d(R) \rho(R) v_R(R) = \dot{M}, \quad (5)$$

where  $H_d(R)$  is the half thickness of the disc,  $\rho(R)$  is the mean density of the disc, and  $v_R(R)$  is the radial velocity of the accretion flow at radius  $R$ .

The equation of state for the gas in the disc is

$$p_{\text{tot}} = p_{\text{gas}} + p_{\text{rad}} = \frac{\rho k T_{\text{disc}}}{\mu m_p} + \frac{1}{3} a T_{\text{disc}}^4, \quad (6)$$

where  $\mu = (1/\mu_i + 1/\mu_e)^{-1}$ ,  $\mu_i = 1.23$  and  $\mu_e = 1.14$  are adopted corresponding to the plasma consisting of 3/4 hydrogen and 1/4 helium. The vertical hydrodynamical equilibrium requires  $H_d = c_s/\Omega_K$ , where the sound speed  $c_s = \sqrt{(p_{\text{tot}} + p_m)/\rho}$ .

The angular momentum equation for the disc is

$$\dot{M} \Omega_K(R) \left[ 1 - \left( \frac{R_{\text{in}}}{R} \right)^{1/2} \right] = 4\pi H_d \tau_{r\varphi}, \quad (7)$$

where the magnetic stress tensor is given by equation (4).

Solving equations (1)-(7) numerically, the structure of the disc and the power dissipated in the corona  $Q_{\text{cor}}^+$  can be derived as functions of radius  $R$ . The ratio of the power dissipated in the corona to the total for such a disc-corona system is available:

$$\langle f \rangle = \frac{\int Q_{\text{cor}}^+ 2\pi R dR}{\int Q_{\text{diss}}^+ 2\pi R dR}. \quad (8)$$

The equation of state for the hot gas in the corona is

$$p_{\text{cor}} = \frac{\rho_{\text{cor}} k T_i}{\mu_i m_p} + \frac{\rho_{\text{cor}} k T_e}{\mu_e m_p} + p_{\text{cor},m}, \quad (9)$$

where  $T_i$  and  $T_e$  are the temperatures of the ions and electrons in the two-temperature corona, and the magnetic pressure  $p_{\text{cor},m} = B_{\text{cor}}^2/8\pi$ . In this work, the magnetic fields are assumed to be equipartition with the gas pressure in the corona. The vertical hydrodynamical equilibrium in the corona requires  $H_{\text{cor}} = c_{\text{cor},s}/\Omega_K$ , where the sound speed  $c_{\text{cor},s} = \sqrt{p_{\text{cor}}/\rho_{\text{cor}}}$ .

The energy equation describing the two-temperature corona is

$$Q_{\text{cor}}^+ = Q_{\text{cor}}^{\text{ie}} + \delta Q_{\text{cor}}^+ = F_{\text{cor}}^-, \quad (10)$$

where  $F_{\text{cor}}^- = F_{\text{syn}}^- + F_{\text{brem}}^- + F_{\text{Comp}}^-$  is the cooling rate in unit surface area of the corona and  $Q_{\text{cor}}^{\text{ie}}$  is the energy transfer rate from the ions to the electrons in the corona via Coulomb collisions, which is given by Stepney & Guilbert (1983). The fraction of the energy directly heat the electrons  $\delta$  can be as high as  $\sim 0.5$  by magnetic reconnection, if the magnetic fields in the plasma are strong (Bisnovatyi-Kogan & Lovelace 1997, 2000). In this work, we adopt  $\delta = 0.5$  in our calculations. For the plasma consisting of different

elements, the Coulomb interaction between the electrons and ions is given by (see Zdziarski 1998)

$$Q_{\text{cor}}^{\text{ie}} = 1.5 \sum_Z \frac{m_e}{m_p A_Z} Z^2 n_e n_Z H_{\text{cor}} \sigma_T c \frac{kT_i - kT_e}{K_2(1/\Theta_e) K_2(1/\Theta_Z)} \ln \Lambda \times \left[ \frac{2(\Theta_e + \Theta_Z)^2 + 1}{\Theta_e + \Theta_Z} K_1 \left( \frac{\Theta_e + \Theta_Z}{\Theta_e \Theta_Z} \right) + 2K_0 \left( \frac{\Theta_e + \Theta_Z}{\Theta_e \Theta_Z} \right) \right], \quad (11)$$

where  $A_Z$  is the mass number of the  $Z$ th element,  $\ln \Lambda = 20$ ,  $\Theta_e = kT_e/m_e c^2$ ,  $\Theta_Z = \Theta_i/A_Z$ , and  $\Theta_i = kT_i/m_p c^2$  are the dimensionless temperatures. Although the cooling rate of the corona is dominated by the Compton scattering of the soft incident photons from the disc, we include the synchrotron, bremsstrahlung and Compton emission in our calculations. The cooling terms  $F_{\text{syn}}^-$  and  $F_{\text{brem}}^-$  are the functions of electron number density, temperature, and the magnetic field strength of the gas in the corona, which are taken from Narayan & Yi (1995).

Assuming the corona to be a parallel plane, the mean probability of the soft photons injected from the cold disc experiencing the first-order scattering in the corona is

$$P_1 = 2 \int_0^1 (1 - e^{-\tau_0 / \cos \theta}) \cos \theta d \cos \theta, \quad (12)$$

where the constant specific intensity of the soft photons from the disc is assumed,  $\theta$  is the angle of the motion of the soft photons with respect to the vertical direction of the disc and  $\tau_0 = \sigma_T n_e H_{\text{cor}}$  is the optical depth of the corona for electron scattering in the vertical direction. For simplicity, we assume the first-order scattered photons are radiated uniformly throughout the vertical direction of the corona. The mean probability for these first-order scattered photons experiencing the second-order scattering can be estimated as

$$P_2 = \frac{1}{2} \int_0^1 d\xi \int_0^1 [1 - e^{-\xi \tau_0 / \cos \theta} + 1 - e^{-(1-\xi) \tau_0 / \cos \theta}] d \cos \theta, \quad (13)$$

where  $\xi = z/H_{\text{cor}}$ , and the first-order scattered photons are assumed to be radiated isotropically. The probability of the scattered photons experiencing next higher order scattering approximates to  $P_2$ , so we simply adopt  $P_n = P_2$  for  $n > 2$ . Thus, using the method suggested by Coppi & Blandford (1990), we can calculate the Comptonized spectrum with equations (12) and (13), if the density, temperature of electrons, and the incident spectrum of the disc are known. Integrating the derived Comptonized spectrum over the frequency, the cooling of the electrons in the corona due to the Compton scattering  $F_{\text{Comp}}^-$  is available.

The disc structure and the power dissipated in the corona can be calculated as functions of  $R$ , provided the black hole mass  $M_{\text{bh}}$ , mass accretion rate  $\dot{M}$  and the viscosity parameter  $\alpha$  are specified. The scaleheight of the corona is a function of  $T_i$ ,  $T_e$ , and  $n_e$ , on the assumption of static hydrodynamical equilibrium in the vertical direction. There are two equations describing the energy equilibrium in the corona at  $R$  (equation 10), which contain three physical quantities of the corona:  $T_i$ ,  $T_e$ , and  $n_e$ . Liu, Mineshige & Ohsuga (2003) calculated the vertical structure of the two-temperature corona above a thin disc based on the evaporation mechanism, and their results show that the temperature of the ions in the corona is always in the range of  $\sim 0.2 - 0.3$  virial temperature (the virial temperature is defined as  $T_{\text{vir}} = GMm_p/kR$  in their work). In this work, we adopt a slightly different definition:  $T_{\text{vir}} = GMm_p/3kR$ , as that adopted by Merloni & Fabian

(2002). To avoid the complexity of calculating the vertical structure of the corona, we simply adopt  $T_i = 0.9T_{\text{vir}}$  [equivalent to 0.3 in Liu, Mineshige & Ohsuga (2003)'s work] in our model calculations. Thus, the structure of the corona, i.e., the temperature and density of the electrons, can be derived, and the spectra of the disc-corona system are available based on the derived disc-corona structure with different magnetic stress tensors given in equation (4).

### 3 RESULTS

We calculate the disc-corona structure as described in section 2. The black hole mass  $M_{\text{bh}} = 10^8 M_{\odot}$  is adopted in all our calculations, because the main features of the hard X-ray spectra are almost independent of  $M_{\text{bh}}$  for massive black holes in AGN. In Fig. 1, we plot the ratios of the power radiated in the corona to the total power  $L_{\text{cor}}/L_{\text{bol}}$  as functions of accretion rate  $\dot{m}$  predicted by the models with different magnetic stress tensors. The dimensionless accretion rate  $\dot{m}$  is defined as  $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$ , where  $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/\eta_{\text{eff}}c^2$ , and a conventional radiative efficiency  $\eta_{\text{eff}} = 0.1$  is adopted. The model with  $\tau_{r\varphi} = \alpha p_{\text{tot}}$  always leads to constant ratios  $L_{\text{cor}}/L_{\text{bol}}$  independent of accretion rate  $\dot{m}$ , while the disc-corona model calculations with  $\tau_{r\varphi} = \alpha p_{\text{gas}}$  show that  $L_{\text{cor}}/L_{\text{bol}}$  becomes extremely small for high accretion rates (e.g.,  $L_{\text{cor}}/L_{\text{bol}} \sim 0.01$  for  $\dot{m} \sim 1$ ). The model with  $\tau_{r\varphi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  shows that the ratios  $L_{\text{cor}}/L_{\text{bol}} \sim 0.3 - 0.6$  at  $\dot{m} = 0.01$ , while  $L_{\text{cor}}/L_{\text{bol}} \sim 0.05 - 0.1$  at  $\dot{m} = 1$ , for different values of  $\alpha$ .

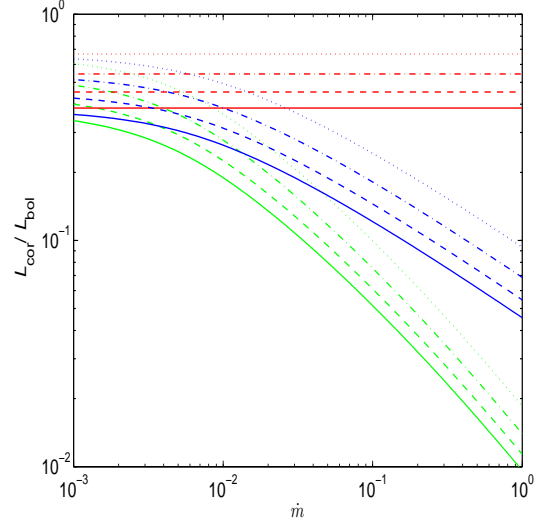
The temperature and optical depth for Compton scattering of the hot electrons in the vertical direction of the corona are plotted in Fig. 2. The electron temperatures are in the range of  $\sim 5 \times 10^8 - 3 \times 10^9$  K for different values of  $\dot{m}$ . The temperature of the hot electrons in the corona tends to decrease with accretion rate  $\dot{m}$ . When the accretion rate  $\dot{m}$  is as high as  $\sim 0.5$ , the electron temperature of the corona decreases to  $\sim 5 \times 10^8$  K.

In Fig. 3, we plot the spectra of the disc-corona systems calculated with different magnetic stress tensors. The hard X-ray emission indeed exhibits a power-law feature for all the models. The photon spectral indices and the ratio of the bolometric luminosity to the X-ray luminosity in 2–10 keV as functions of accretion rate for different magnetic stress models are plotted in Fig. 4. The photon indices  $\Gamma$  do not change much with accretion rate  $\dot{m}$  for the disc-corona models with either  $\tau_{r\varphi} = \alpha p_{\text{tot}}$  or  $\tau_{r\varphi} = \alpha p_{\text{gas}}$ , while the hard X-ray spectral index  $\Gamma$  increases significantly with accretion rate  $\dot{m}$  for the model with  $\tau_{r\varphi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$ .

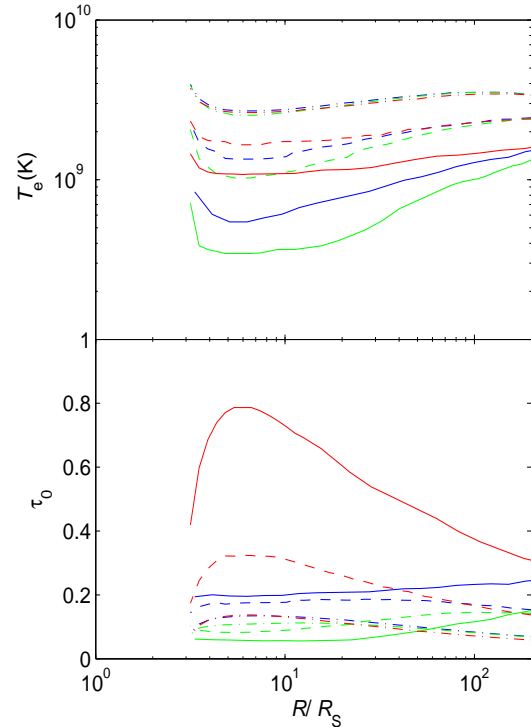
We compare the spectra of the accretion disc/corona systems with different ion temperature  $T_i$  adopted in Fig. 5. It is found that the X-ray spectra change little with the value of  $T_i$ , provided all other parameters are fixed. In Fig. 6, we plot the Compton  $y$ -parameter ( $y = 4kT_e\tau_0/m_e c^2$ ) varying with  $T_i$ , and find that it is insensitive to  $T_i$ .

### 4 DISCUSSION

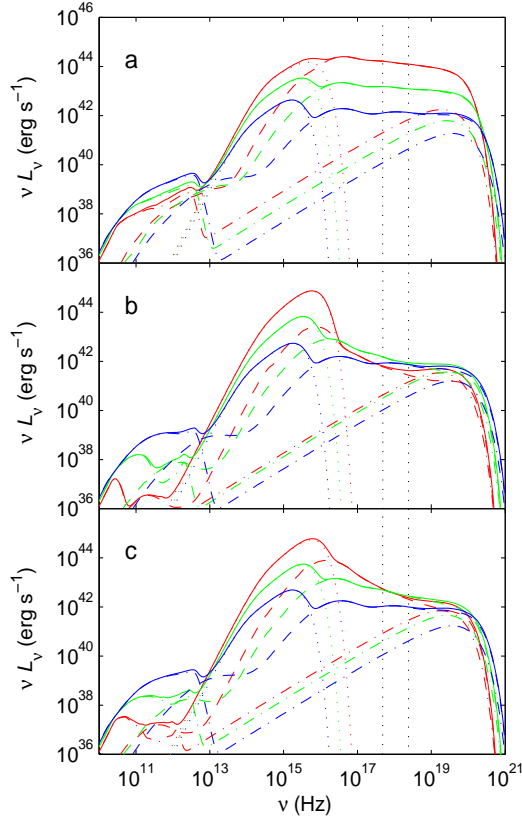
It is believed that the power generated in the disc is transported vertically with the buoyancy of the magnetic fields in the disc, and the fraction of the power dissipated in the corona to the total is mainly regulated by the magnetic fields (e.g., Di Matteo 1998; Merloni & Fabian 2002; Wang, Watarai & Mineshige 2004). Vasudevan & Fabian (2007) found that the fraction  $L_{\text{cor}}/L_{\text{bol}}$  is about 0.5 for the sources with low Eddington ratio  $L_{\text{bol}}/L_{\text{Edd}} \sim$



**Figure 1.** The ratios  $L_{\text{cor}}/L_{\text{bol}}$  as functions of accretion rate  $\dot{m}$  predicted by the models with different magnetic stress tensors. The red lines represent the results calculated with the magnetic stress tensor  $\tau_{r\varphi} = \alpha p_{\text{tot}}$  (green lines:  $\tau_{r\varphi} = \alpha p_{\text{gas}}$ ; blue lines:  $\tau_{r\varphi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$ ). The different line types represent the different values of viscosity parameter  $\alpha$  adopted (solid lines:  $\alpha = 0.2$ ; dashed lines:  $\alpha = 0.3$ ; dash-dotted lines:  $\alpha = 0.5$  and dotted lines:  $\alpha = 1$ ).



**Figure 2.** The upper panel: the temperature of the electrons in the corona as functions of disc radius  $R$ . The colours represent the models with different magnetic stress tensors, which are the same as those in Fig. 1. The solid lines represent the results calculated for  $\dot{m} = 0.5$ , while the dashed and dash-dotted lines are for  $\dot{m} = 0.05$  and  $0.005$ , respectively. The viscosity parameter  $\alpha = 0.5$  is adopted for all the model calculations. In the lower panel, we plot the optical depth for the Compton scattering of the electrons in the vertical direction of the corona.

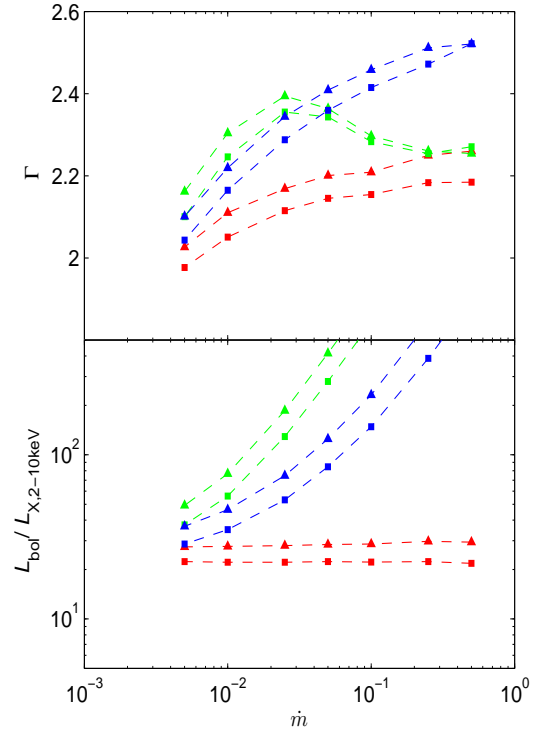


**Figure 3.** The spectra of the disc-corona systems with different magnetic stress tensors (a:  $\tau_{r\phi} = \alpha p_{\text{tot}}$ ; b:  $\tau_{r\phi} = \alpha p_{\text{gas}}$ ; c:  $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$ ). In all the calculations,  $\alpha = 0.5$  is adopted. The dotted lines represent the spectra of the cold discs, while the dashed and dash-dotted lines are for the Compton and synchrotron+bremsstrahlung radiation respectively. The accretion rates:  $\dot{m} = 0.5$  (red),  $0.05$  (green) and  $0.005$  (blue) are adopted respectively (from up to down). The two black dotted lines represent 2 and 10 keV, respectively.

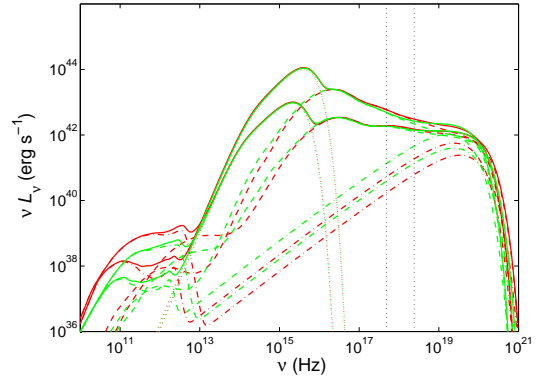
0.01, while it decreases to 0.1 for  $L_{\text{bol}}/L_{\text{Edd}} \sim 1$ , for a sample of AGN. From Fig. 1, we find that the model with  $\tau_{r\phi} = \alpha p_{\text{tot}}$  always predict a constant  $L_{\text{cor}}/L_{\text{bol}}$ , which seems to be inconsistent with the observation. The models with other two magnetic stress tensors can roughly reproduce the trend of  $L_{\text{cor}}/L_{\text{Edd}}$  decreasing with accretion rate  $\dot{m}$ , though the model with  $\tau_{r\phi} = \alpha p_{\text{gas}}$  always underpredicts the  $L_{\text{cor}}/L_{\text{bol}}$  at high Eddington ratio end, even if  $\alpha = 1$  is adopted. It seems that the model with  $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  is better than the other two models.

The ratio  $L_{\text{cor}}/L_{\text{bol}}$  decreases with accretion rate  $\dot{m}$ , which means the fraction of the power radiated from the cold disc increases with  $\dot{m}$ . The cooling mechanism of the hot corona is dominated by the inverse Compton scattering of the soft photons from the cold disc by the hot electrons in the corona. There are more soft photons supplied by the cold disc for high- $\dot{m}$  cases, and the fraction of the power radiated from the corona decreases with  $\dot{m}$ . Thus, it can be easily understood that the temperature of the hot electrons in the corona should decrease with accretion rate  $\dot{m}$  (see Fig. 2). It is found that the temperature of the electrons in the corona decreases to  $\sim 3 - 4 \times 10^8$  K for the models with  $\tau_{r\phi} = \alpha p_{\text{gas}}$  or  $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  when  $\dot{m} = 0.5$ , which implies that the hot corona is nearly to be suppressed when  $\dot{m}$  is as high as  $\gtrsim 0.5$ .

We calculate the spectra of the accretion disc-corona systems, and find that their hard X-ray continuum emission indeed exhibits

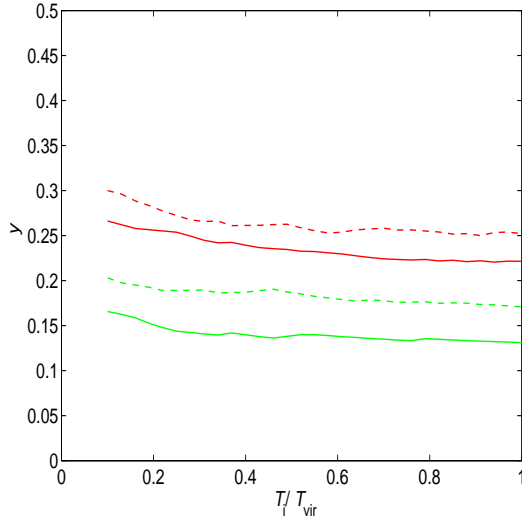


**Figure 4.** The upper panel: the photon spectral indices as functions of accretion rate  $\dot{m}$  for different magnetic stress models (red:  $\tau_{r\phi} = \alpha p_{\text{tot}}$ ; green:  $\tau_{r\phi} = \alpha p_{\text{gas}}$ ; blue:  $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$ ). The squares represent the results calculated with  $\alpha = 0.5$ , while the triangles are for  $\alpha = 0.3$ . The X-ray bolometric correction factors  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  as functions of accretion rate  $\dot{m}$  for different models are plotted in the lower panel.



**Figure 5.** The spectra of the disc corona systems calculated for  $\dot{m} = 0.01$ , and  $0.1$ , respectively ( $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  is adopted in the calculations). The red lines represent the spectra for  $T_i = 0.9 T_{\text{vir}}$ , while the green lines are for  $T_i = 0.3 T_{\text{vir}}$ . The dotted lines represent the spectra of the cold discs, while the dashed and dash-dotted lines are for the Compton and synchrotron+bremsstrahlung radiation respectively.

a power-law spectrum (see Fig. 3). In Fig. 4, we plot the photon spectral indices  $\Gamma$  in 2–10 keV and the X-ray correction factors  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  as functions of accretion rate  $\dot{m}$  with different magnetic stress tensors. We find that the photon spectral index  $\Gamma$  predicted by the model with  $\tau_{r\phi} = \alpha p_{\text{tot}}$  is within  $\sim 2 - 2.2$  for different values of  $\dot{m}$ , and it increases slightly with  $\dot{m}$ . The X-ray correction factor  $L_{\text{bol}}/L_{\text{X},2-10\text{keV}}$  remains constant with accretion rate  $\dot{m}$  for this model. The photon spectral index  $\Gamma$  increases



**Figure 6.** The Compton  $y$ -parameter versus the ion temperature  $T_i$  in the corona at radius  $R$  with different accretion rates  $\dot{m} = 0.01$  (red), and  $0.1$  (green). The solid lines are calculated with  $R = 10R_S$ , while the dashed lines are for  $R = 40R_S$ .

with  $\dot{m}$  while  $\dot{m} \lesssim 0.02$ , and it then decreases with  $\dot{m}$ , for the model with  $\tau_{r\phi} = \alpha p_{\text{gas}}$ . We find that the bremsstrahlung emission contributes some to the hard X-ray energy band when  $\dot{m}$  is high, and the photon spectral index  $\Gamma$  is slightly affected by the bremsstrahlung emission (see the middle panel of Fig. 3). We find that the X-ray correction factor  $L_{\text{bol}}/L_{X,2-10\text{keV}}$  for this model becomes extremely high for high- $\dot{m}$  cases, which seems to be inconsistent with that derived from the observations (see Fig. 12 in Vasudevan & Fabian 2007). The X-ray spectra of the disc-corona systems with  $\tau_{r\phi} = \alpha \sqrt{p_{\text{gas}} p_{\text{tot}}}$  show that both the photon spectral index  $\Gamma$  and the X-ray correction factor  $L_{\text{bol}}/L_{X,2-10\text{keV}}$  increase with accretion rate  $\dot{m}$ , which are qualitatively consistent with the observations, except for the low  $\dot{m}$  end. The temperature of the electrons in the corona decreases with  $\dot{m}$  (see Fig. 2), and the inverse Compton scattered X-ray spectrum therefore becomes softer for a higher  $\dot{m}$ . Similarly, anticorrelations between the X-ray spectral indices and X-ray fluxes were found in some X-ray binaries (e.g., Yu et al. 2003; Zdziarski et al. 2004; Del Santo et al. 2008), which seem to be roughly consistent with our present disc corona model.

The photon spectral index  $\Gamma$  is found to increase with the Eddington ratio, and it could be as low as  $\sim 1$  when  $\dot{m} \sim 0.01$  (see Shemmer et al. 2006, 2008). The hard X-ray photon spectral index  $\Gamma \sim 2$  derived from our model calculations with any magnetic stress tensor when  $\dot{m} \sim 0.01$ , which are significantly higher than the observed  $\Gamma \sim 1$  (e.g. Shemmer et al. 2006, 2008). Although the patchy corona model proposed by Haardt, Maraschi & Ghisellini (1994) can produce the observed hard X-ray spectra with  $\Gamma \sim 1$ , this patchy corona model is unable to explain the correlation between the Compton reflection and the hard X-ray spectral index. In an alternative model, the hot plasma above the cold disc is assumed to move away from the cold disc at a mild relativistic velocity (Beloborodov 1999), which reduces both the reflection and reprocessing in the cold disc. This naturally leads to harder X-ray spectrum (see the discussion in Sect. 1). However, the detailed physics for producing such mildly relativistic outflows is still unclear.

It was argued that the central engines in these low-luminosity sources with very hard X-ray emission may be different from their

high-luminosity counterparts, i.e., the advection dominated accretion flows (ADAFs) may be present in these low-luminosity sources (Lu & Yu 1999). The soft incident photons for Comptonization are mainly due to the synchrotron+bremsstrahlung emission in the ADAFs. The energy density of the soft photons in the ADAF is much lower than that in the disc-corona model, which leads to inefficient cooling and relatively higher electron temperature in the ADAFs (e.g., Narayan & Yi 1995). Thus, the X-ray spectra of the ADAFs can be much harder than those of the disc-corona systems. The very hard X-ray spectra observed in these low luminosity sources can be well modelled with the ADAFs accreting at low rates (see e.g., Quataert et al. 1999; Xu & Cao 2008, for the spectral modeling for the hard X-ray emission from the low luminosity AGN with ADAFs). Our present model calculations are limited to the disc-corona model, in which the cold discs extend to the marginal stable orbits. The model of a disc-corona connecting with inner ADAF may resolve the photon index discrepancy at the low  $\dot{m}$  end. The geometry of this ADAF+disc/corona scenario is quite similar to the hot plasma+cold disc model proposed by Zdziarski, Lubinski & Smith (1999). When the accretion rate decreases to a critical value  $\dot{m}_{\text{crit}}$ , the inner cold disc may be truncated at radius  $R_{\text{tr}}$  and it transits to an ADAF within this radius. The transition radius  $R_{\text{tr}}$  may be close to the marginal stable orbits soon after the accretion mode transition (e.g., Quataert et al. 1999; Yuan & Narayan 2004; Xu & Cao 2008), and then it may increase with decreasing accretion rate  $\dot{m}$  (e.g., Liu et al. 1999; Rozanska & Czerny 2000; Spruit & Deufel 2002; Yuan & Narayan 2004). The X-ray spectrum of such an ADAF+disc/corona system consists of emission from the inner ADAF and outer corona. The ratio of the X-ray emission from the ADAF to that from the corona increases with decreasing  $\dot{m}$ , and therefore the photon spectral index  $\Gamma$  may decrease smoothly with decreasing  $\dot{m}$  provided the initial truncated radius of the cold disc is not very large compared with the marginal stable orbits. Similar to Zdziarski, Lubinski & Smith (1999)'s model, the correlation between the Compton reflection and the hard X-ray spectral index can also be naturally explained by this ADAF+disc/corona model, if the truncated radius  $R_{\text{tr}}$  increases with decreasing accretion rate  $\dot{m}$ . This model can also successfully explain the spectral behaviours of X-ray binaries (see Done, Gierlinski & Kubota 2007, for a review and references therein). The detailed calculations on such ADAF+corona systems will be reported in our future work.

In this work, we simply assume  $T_i = 0.9T_{\text{vir}}$ , motivated by the previous work on the disc-corona model calculations (Liu, Mineshige & Shibata 2002; Liu, Mineshige & Ohsuga 2003). We also check how  $T_i$  may affect our results by tuning the value of  $T_i$ , and find that the X-ray spectra of the disc/corona systems change very little if all other disc parameters are fixed (see Fig. 5). The cooling of the corona is dominated by the inverse Compton radiation, which is roughly proportional to Compton  $y$ -parameter. Thus, it is not surprising that our calculations show the Compton  $y$ -parameter varying little with  $T_i$  if all other parameters are fixed (see equation 10 and Fig. 6). The thickness of the corona is mainly regulated by the ion temperature  $T_i$ , and therefore the electron density decreases with increasing  $T_i$ , which leads to significant difference in synchrotron/bremsstrahlung spectra for different  $T_i$  (see Fig. 5). We find that the resulted  $\dot{m} - \Gamma$  relations are almost not changed if a different value of  $T_i$  is adopted. Unlike the ADAFs, almost all the power dissipated in the hot corona with magnetic reconnection is radiated away locally. This means the radiated power in the corona is independent of the value  $\delta$ , and the temperature and density of the electrons in the corona are almost insensitive with the value of

$\delta$ . We also perform the same model calculations for different black hole masses (e.g.,  $M_{\text{bh}} = 10^9 M_{\odot}$ ). It is found that our results are almost independent of  $M_{\text{bh}}$  for massive black holes.

In all our calculations, we assume the magnetic fields to be equipartitioned with the gas pressure in the corona. As the cooling of the corona is dominated by the inverse Comptonization of the soft photons from the cold disc, the structure of the disc-corona and its spectrum (except in the radio wavebands) is almost independent of the magnetic field strength in the corona. Recently, Laor & Behar (2008) found there is a strong correlation between the radio luminosity ( $L_{\text{R}}$ ) and X-ray luminosity ( $L_{\text{X}}$ ) with  $L_{\text{R}} \sim 10^{-5} L_{\text{X}}$ , for the radio quiet Palomar-Green (PG) quasar sample. The spectra of our disc-corona model show that the radio emission is correlated with the X-ray emission, which is roughly consistent with the correlation between  $L_{\text{R}}$  and  $L_{\text{X}}$  discovered by Laor & Behar (2008).

## ACKNOWLEDGMENTS

I thank the referee, Zdziarski A. A., for his helpful suggestions/comments, B. F. Liu, T. G. Wang, Q. W. Wu and W. Yuan for helpful discussion. This work is supported by the NSFC (grants 10773020, 10821302 and 10833002), the CAS (grant KJCX2-YW-T03), and the National Basic Research Program of China (grant 2009CB824800).

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